IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of:
Bryan M. Cantrill

Application No.: 10/713,612 Confirmation No.: 7007

Filed: November 14, 2003 Art Unit: 2191

For: SEPARATION OF DATA FROM METADATA IN A TRACING FRAMEWORK Examiner: Phillip H. Nguyen

DECLARATION PURSUANT TO 37 C.F.R. § 1.131

In connection with Applicant's Response to the Office Action issued on December 19, 2006, this declaration sets forth the pertinent facts proving conception and actual reduction to practice of the claimed invention prior to **June 27, 2003**.

1. I, Bryan Cantrill, am the sole inventor listed on U.S. Patent Application Serial No. 10/713,612 entitled "SEPARATION OF DATA FROM METADATA IN A TRACING FRAMEWORK" filed on November 14, 2003.
2. I conceived and completed the actual reduction to practice of the claimed invention at least prior to June 27, 2003, when I gave an internal company speech directed, in part, to the claimed invention.
3. The speech, which was conducted on March 12, 2002, included a slide presentation and a live demonstration of the claimed invention. A copy of the slide presentation entitled "DTrace: Dynamic Tracing For Solaris" dated March 11, 2002 is included under Tab 1. Further, a DVD video of the speech showing the live demonstration is attached under Tab 2.

4. The relevant portion of the DVD Video particularly related the subject matter of the referenced application is: 00:37:50 – 03:15:18. The aforementioned times are listed in the following format HH:MM:SS.
5. A concise mapping of the claims to the slide presentation and the DVD video is included under Tab 3.
6. All events related to the conception and completion of the actual reduction to practice of the claimed invention were performed in the United States.

I, Bryan M. Cantrill, hereby declare that all statements made herein of my own knowledge are true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Signed this day 19, of March 2007

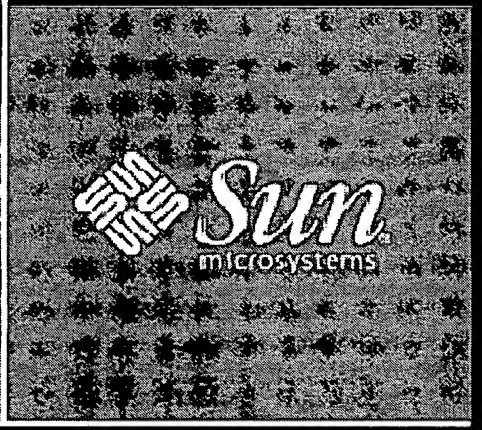
Bryan Cantrill w/ permission

Bryan M. Cantrill

Aly Dossa
3/19/07.

TAB 1

Solaris RAS/Performance

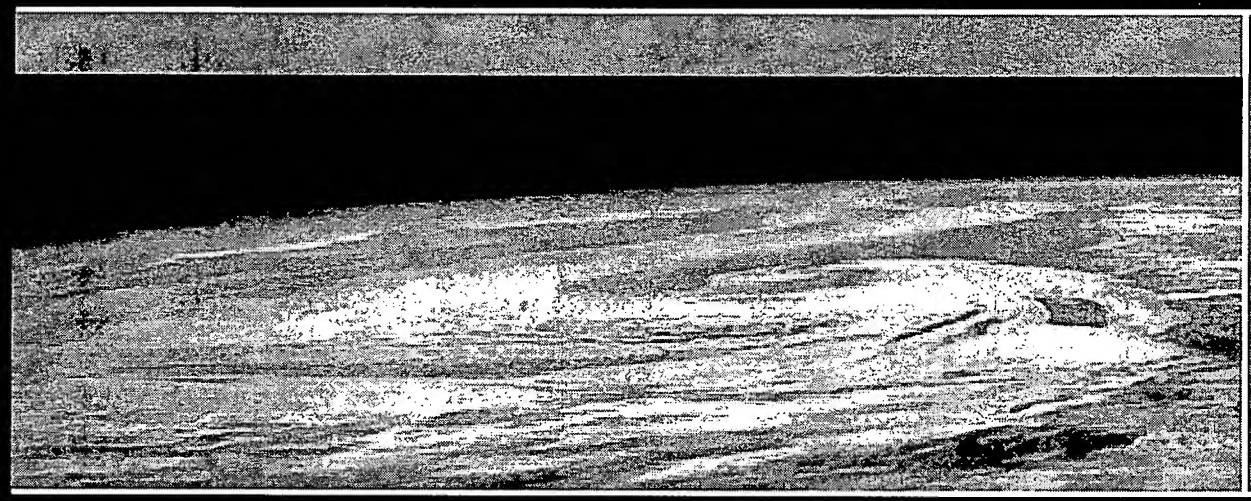


DTrace: Dynamic Tracing For Solaris

Bryan Cantrill (bmc@eng)

Mike Shapiro (mws@eng)

Solaris Kernel Technologies



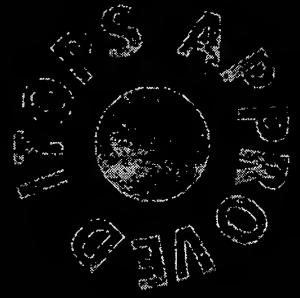
Solaris RAS/Performance

Sun microsystems

DTrace: Dynamic Tracing For Solaris

Bryan Cantrill (bc30992@japan)
Mike Shapiro (ms36066@sfbay)

Solaris Kernel Technologies



Sun microsystems

A Modern Tracing Framework

- Must have zero probe effect when disabled
- Must allow for novel tracing technologies
- Must allow for thousands of probes
- Must allow arbitrary numbers of consumers
- Unwanted data must be pruned as early as possible in the data chain
- Data must be coalesced whenever possible, and as early as possible

Sun microsystems

The DTrace Vision

- Build a tracing framework that provides concise answers to arbitrary questions
- Enable quantum leap in performance analysis and engineering
- Improve RAS through continuous tracing
- Accelerate project development
- Eliminate DEBUG and other special kernels: *all* facilities available in production

IBM MVS Tracing

- MVS provided wealth of tracing facilities, notably GTF and CTRACE
- IPCS console provided commands to enable, filter, and display GTF, CTRACE trace records
- Extensive probes provided for base operating system, channel programs
- GTRACE() assembler macro used to record data in a user program; can later be merged

GTF Example

- Operator console:

```
START GTF.EXAMPLE1
AHL103I TRACE OPTIONS SELECTED--SYSM,USR,DSP
00 AHL125A RESPECIFY TRACE OPTIONS OR REPLY U
REPLY 00,U
AHL031I GTF INITIALIZATION COMPLETE
```

- IPCS GTFTRACE output:

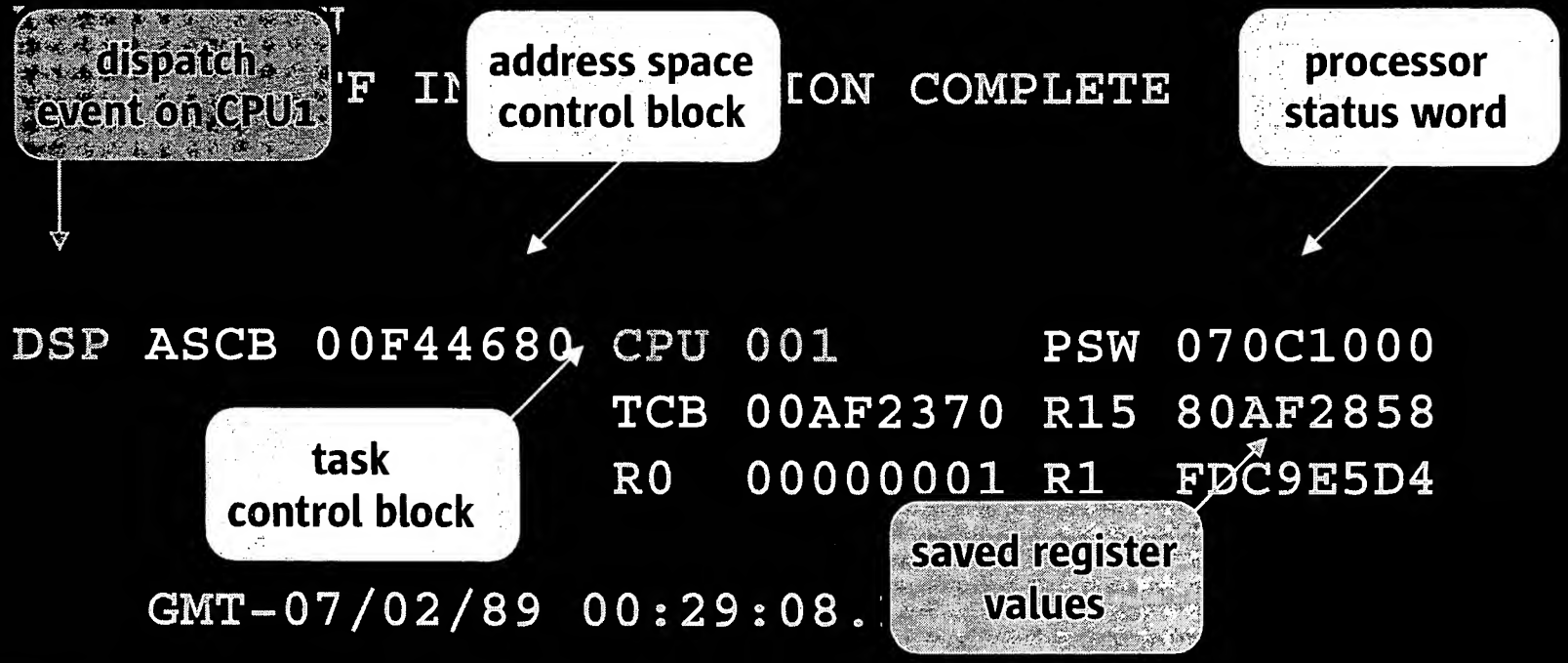
```
DSP ASCB 00F44680 CPU 001       PSW 070C1000
                  TCB 00AF2370 R15 80AF2858
                  R0  00000001 R1  FDC9E5D4

     GMT-07/02/89 00:29:08.155169
```

GTF Example

- Operator console:

```
START GTF.EXAMPLE1
AHL103I TRACE OPTIONS SELECTED--SYSM,USR,DSP
00 AHL125A RESPECIFY TRACE OPTIONS OR REPLY U
```



Sun microsystems

VTRACE

- Kernel tracing framework developed early in Solaris 2 (1991)
- Provided a C macro to designate a probe site; some probe effect even when disabled
- Additionally, applications could issue fast trap to record events in in-kernel buffer
- In-kernel buffers could be continuously read out and streamed to disk

Sun microsystems

VTRACE, cont.

- Scalable and lightweight when enabled
- Fair coverage: ≈1,000 trace points
- Used to solve real performance problems
- As a result of disabled probe effect, required a special kernel
- Fell into disrepair during 64-bit port

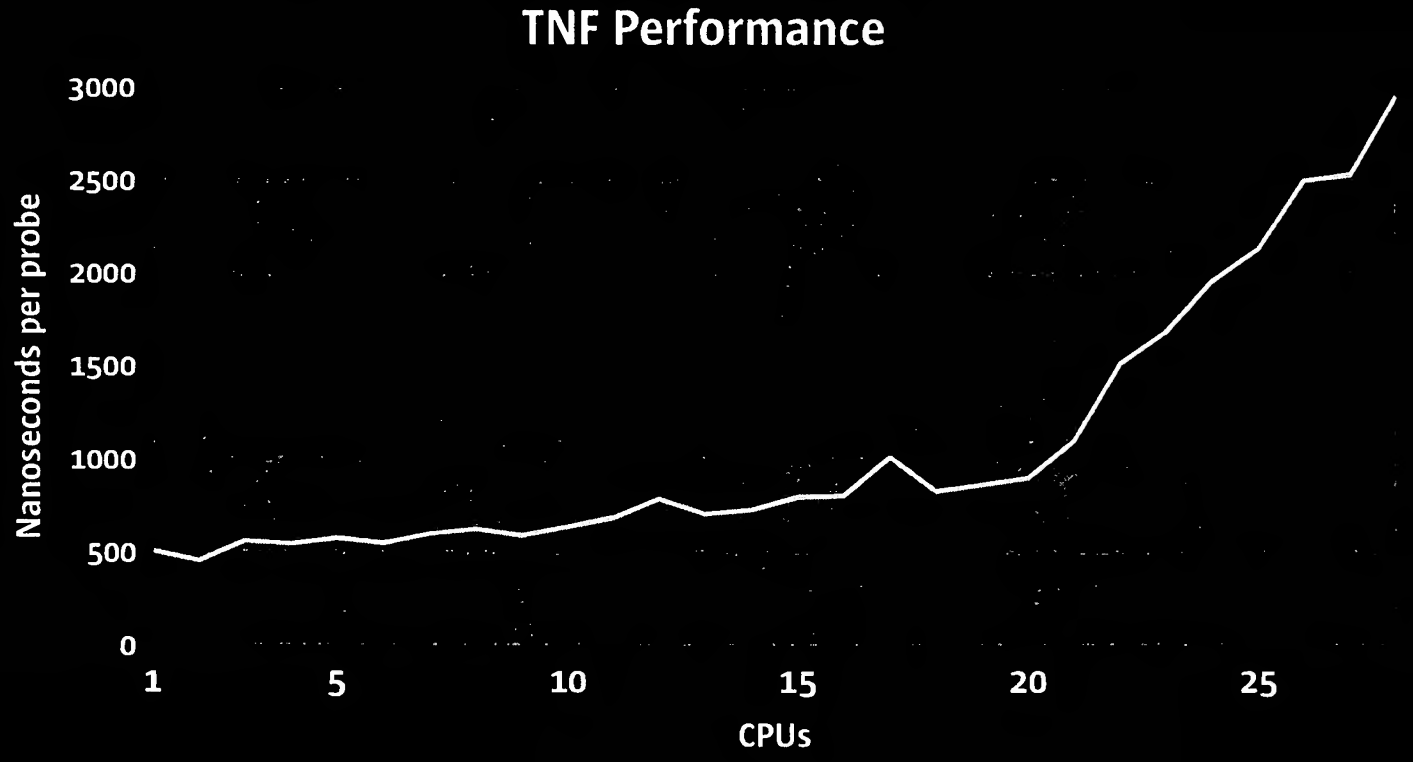
TNF

- *Trace Normal Form* tracing framework introduced in Solaris 2.5
- Originally a user-level framework (LSARC 1993/650); kernel support tacked on (PSARC 1994/165)
- Like VTRACE, provides C macro to designate a probe site; induces load, compare and branch even if disabled

Sun microsystems

TNF, cont.

- Uses pseudo per-CPU buffering, resulting in suboptimal CPU scaling



Sun microsystems

TNF, cont.

- Some of TNF's failings:
  - Too few probes (≈30 probes in common kernel code)
  - Crude filtering (only based on process ID, and even then doesn't work for scheduling events)
  - No control over data generated by each probe
  - Doesn't allow for continuous collection of data
  - Doesn't correlate kernel data to application activity
  - Bizarre data format designed for use only in postmortem analysis

Sun microsystems

KernInst

- Kernel instrumentation tool developed at Wisconsin [Tamches, Miller, et al.]
- User-level daemon performs run-time register analysis of kernel object code
- Code patches, trampoline code, and instrumentation are inserted using driver
- Overcomplicated by living outside of core OS
- Does not provide sufficient predicate support
- Unsafe probe insertion causes OS failure!

Sun microsystems

Linux DProbes

- Dynamic instrumentation kit for Linux kernel [Moore, IBM LTC, et al.]
- Replaces kernel text with breakpoint trap that vectors to user RPN probe program
- Also provides access to Intel debug registers
- Currently under active development
- DProbes facility not part of stock kernel
- Significant safety issues (more later ...)

Sun microsystems

Competitive Landscape

Feature	GTF	vtrace	TNF	KInst	DProbe	Notes
user/kernel/merged	M	M	M	K	K	users want combined timeline of user and kernel events
probe coverage	●	◒	✕	◒	◒	framework must provide sufficient probes to solve most problems
disabled probe effect	○	✕	○	●	●	ideal framework has zero probe effect when disabled
scalability	○	●	○	○	○	concurrent probe firings must scale to arbitrary number of CPUs
safety	●	●	◒	✕	✕	no way for user to induce fatal machine or OS failure
extensibility	◒	○	○	◒	◒	framework should allow easy addition of probes and providers
data filtering	●	✕	✕	○	●	users should be able to filter on arbitrary conditions at probe site
arbitrary recording	✕	✕	✕	○	●	users should be able to record arbitrary data on probe firing
self describing	◒	○	◒	✕	✕	type information available to consumers for all recorded data
run-time analysis	●	✕	✕	●	◒	run-time analysis tools should be provided, not just post-mortem
stock availability	●	✕	●	◒	◒	tracing facilities must be available on production systems
stable abstractions	◒	◒	●	✕	✕	framework must provide stable abstractions for layered tools

Sun microsystems

Providers

- Tracing frameworks have historically been tied to a single tracing methodology
- Conversely, new tracing methodologies have had to invent their own frameworks
- In DTrace, the tracing framework is formally separated from tracing *providers*
- Allows for faster adoption of and provides significant leverage for novel tracing methodologies

Sun microsystems

Probes

- A trace point in DTrace is called a *probe*
- A probe is identified by a tuple consisting of Provider, Module, Function and Name
- Probes may have Module and Function unspecified (such probes are said to be *unanchored*)
- Each probe has a unique 32-bit ID

Sun microsystems

Predicates and Actions

- Idea: Provide flexible boolean expressions that can control tracing activities, e.g.

```
if (pid == process of interest)
     then trace data of interest
```

- Must allow completely arbitrary queries to be formulated by user or layered tool
- Must evaluate at probe firing time to prune data stream at earliest opportunity

Sun microsystems

Provider Interface

- Provider makes available all known probes
- Framework calls into provider to enable a specific probe
- Framework handles multiplexing of multiple consumers of a single probe
- Provider indicates that an enabled probe is hit by calling **`dtrace_probe`**(), specifying probe ID

Sun microsystems

dtrace_probe()

- **dtrace_probe**() is called to take appropriate actions (if any) when an enabled probe is hit
- Can be called from any context in which C may be called, e.g.:
  - From high-level interrupt context
  - While interrupts are disabled
  - In synchronization primitives (e.g. **mutex_enter**())
  - While dispatcher locks are held

Sun microsystems

dtrace_probe(), cont.

- Disables interrupts for its duration
  - Substantially simpler than implementing lock-free data structures
  - Prevents preemption, CPU migration
  - As fast as performing an atomic memory operation
  - Synchronous cross calls can be used to guarantee that no threads remain in critical section
- Converts probe ID to internal data structure for further processing

Sun microsystems

dtrace_probe(), cont.

- Iterates over a per-probe chain of *enabling control blocks* (ECBs)
- Each ECB corresponds to an *enabling* of a probe
- The ECB abstraction allows:
  - A given consumer to have multiple, different enablings of a single probe
  - Disjoint consumers to have disjoint enablings of a single probe

Sun microsystems

Enabling Control Blocks

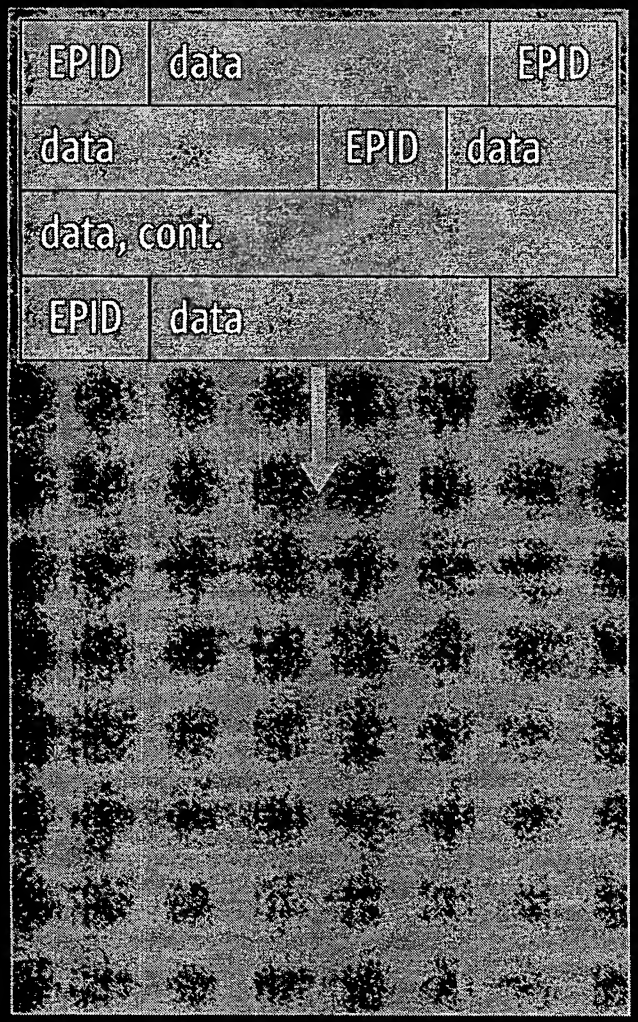
- Each ECB contains:
  - An optional *predicate*
  - A list of one or more *actions*
  - A pointer to an array of per-CPU *buffers*
- Each ECB has a corresponding *enabled probe ID* (EPID)
- EPID space is per consumer

Enabling Control Blocks, cont.

- Actions are taken on an ECB if and only if:
  - There does not exist a predicate, or
  - The predicate evaluates to a non-zero value
- Actions may identify data to be stored into a *trace record*
- Actions need not generate trace data
  - May update variable state (more later)
  - May affect system state in a defined way (e.g. BREAKPOINT, PANIC)

Sun microsystems

Trace Records



- Record size is *constant* per ECB (and therefore per EPID)
- Records consist of 32-bit EPID, followed by some amount of data
- Library determines record size and layout using a separate EPID dictionary

Sun microsystems

Trace Records, cont.

- Library's EPID dictionary can be built dynamically: as a new EPID is seen in the data stream, the library queries for the corresponding record size and layout
- Separating the data stream from the metadata stream facilitates run-time analysis tools
- Lack of data/metadata separation is a serious deficiency in TNF

Buffers

- Buffers are per consumer, per CPU
- Buffers are always allocated in pairs: an *active* buffer and a *spare* buffer
- A buffer is consumed by:
  - Issuing a synchronous cross call to the corresponding CPU to *switch* active buffer with spare buffer
  - Copying out used portion of newly spare buffer (formerly the active buffer) to user-level

Sun microsystems

Buffer Management

- If buffer is full when a data-generating action is taken, a per-buffer *drop count* is incremented and no action is taken
- It is up to consumers to minimize drop counts by reading buffers sufficiently often
- Drop counts are copied out to user-level alongside buffer data; consumers always know if data is incomplete

Sun microsystems

Buffer Management, cont.

- A consumer may optionally indicate that a buffer is to be treated as a *ring buffer*
- Ring buffers wrap on overflow, writing over older data
- Consumers can avoid data loss by reading buffer sufficiently often
- Useful primarily to provide "black box" style event recording

Sun microsystems

Function Boundary Tracing

- Would like a probe before every function entry and after every function return
- Would like to implement probes by hot patching kernel text only when enabled -- thereby avoiding performance effect when disabled
- But how to hot patch text?

Branch Insertion?

- Idea is to patch probe point to be an annulled branch-always into a jump table
- Must perform static analysis to ascertain dead registers
- Analysis must somehow statically determine trap level; failure to do so can induce RED state exception
- e.g. KernInst

Sun microsystems

Software Trap Insertion?

- Idea is to patch desired code to be a trap-always instruction
- Must perform static analysis to avoid placing trap-always instruction where trap level can be non-zero
- Failure to do so can induce RED state exception
- e.g. Hot Diagnosis

Sun microsystems

Branch Insertion, revisited

- If we *only* patch a function's initial save instruction, we solve both of the problems with branch insertion:
  - Trap level is implicitly considered: code at TL > 0 may not arbitrarily issue a save
  - Register analysis is obviated by the save: immediately after the save, locals and outputs are dead

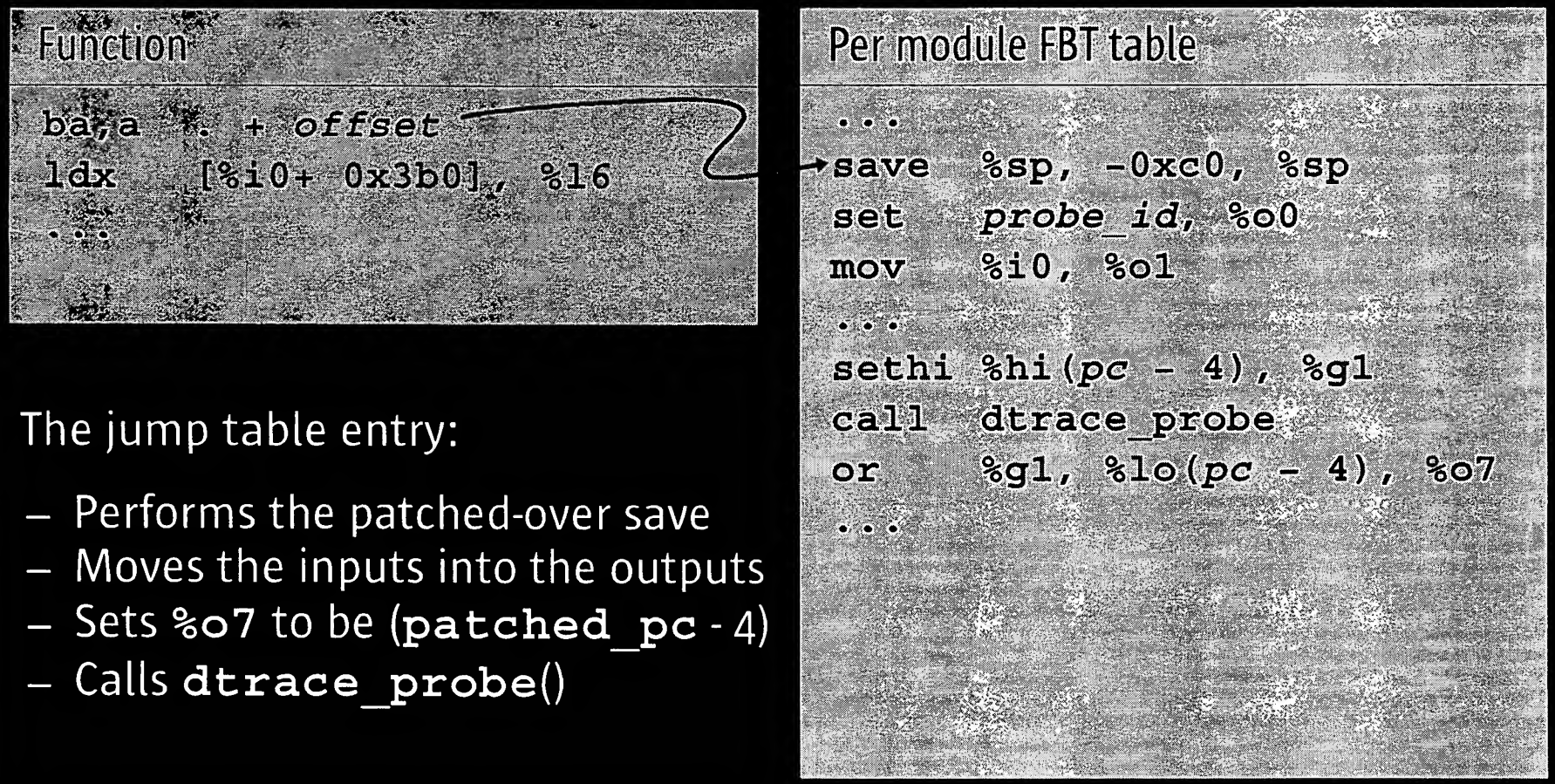
Entry Patching

Function

```
save   %sp, -0xc0, %sp
ldx    [%i0+ 0x3b0], %l6
...
```

We patch the save instruction to be an annulled branch-always into a per-probe entry in a per-module jump table

Entry Patching



The jump table entry:

- Performs the patched-over save
- Moves the inputs into the outputs
- Sets `%o7` to be (`patched_pc` - 4)
- Calls `dtrace_probe`()

Entry Patching, cont.

Function

```
sethi %hi(0x1494800),%g2
sethi %hi(0x140a000),%g1
save %sp, -0xb0, %sp
ldx   [%g2 + 0x98],%g3
...
```

- The first instruction of a non-leaf function is not always a save instruction

- Correctly patching the save instruction in this case would require static register analysis: live registers volatile across the call to **`dtrace_probe`**() must be preserved

Entry Patching, cont.

- We instead patch the first instruction to be the annulled branch-always
- In this case, the jump table entry:
  - Performs a **`MINFRAME`** save
  - Moves the inputs into the outputs
  - Calls **`dtrace_probe`**()
  - Performs a restore
  - Branches back to (**`patched_pc`** + 4) with the patched-over instruction in the delay slot

Sun microsystems

Entry Patching, cont.

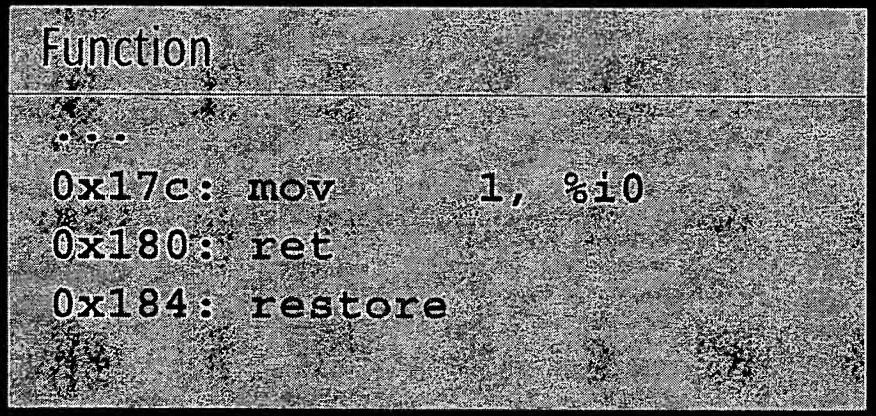
Function

```
ba,a  .  + offset
sethi  %hi(0x140a000),%g1
save   %sp, -0xb0, %sp
ldx    [%g2 + 0x98], %g3
...
```

Per module FBT table

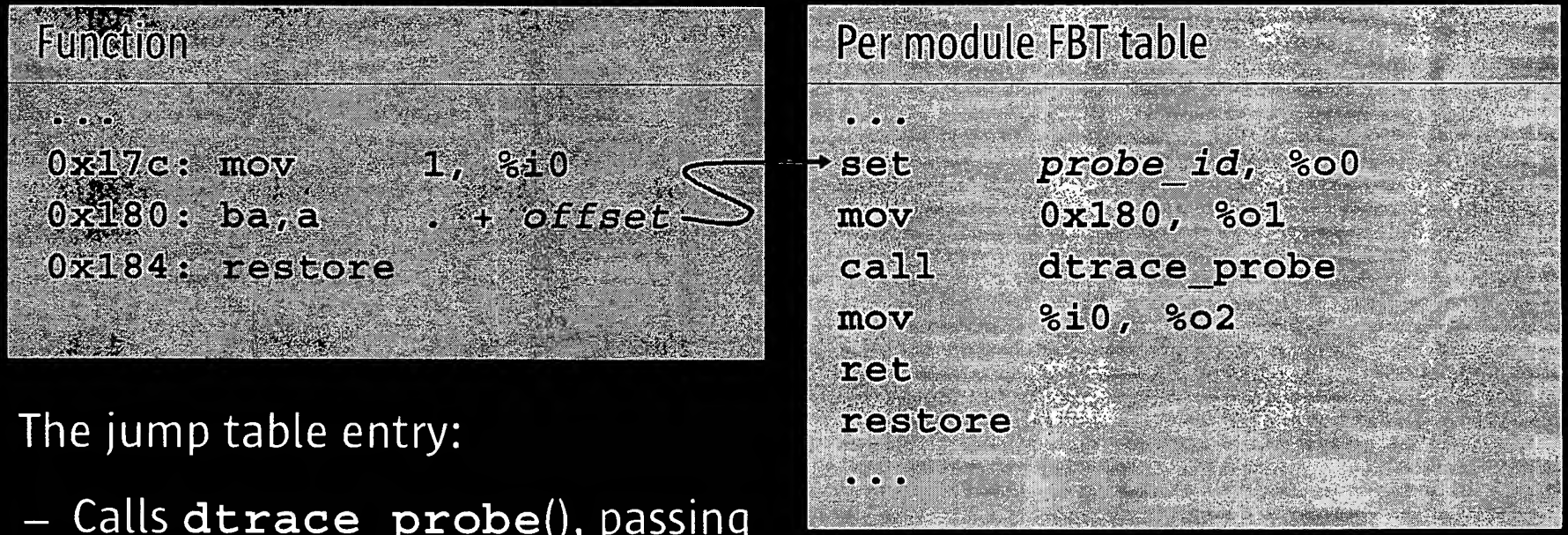
```
...
save     %sp, -MINFRAME, %sp
set      probe_id, %o0
mov      %i0, %o1
...
call     dtrace_probe
mov      %i4, %o5
restore
ba       . + offset
sethi    %hi(0x1494800), %g2
...
```

Return Patching



- ret/restore couplets can be patched in much the same way as save instructions
- The ret is patched to be an annulled branch-always into a jump table entry

Return Patching, cont.



The jump table entry:

- Calls **dtrace_probe**(), passing both the return value and the offset of the ret
- On return from **dtrace_probe**(), performs the ret/restore couplet

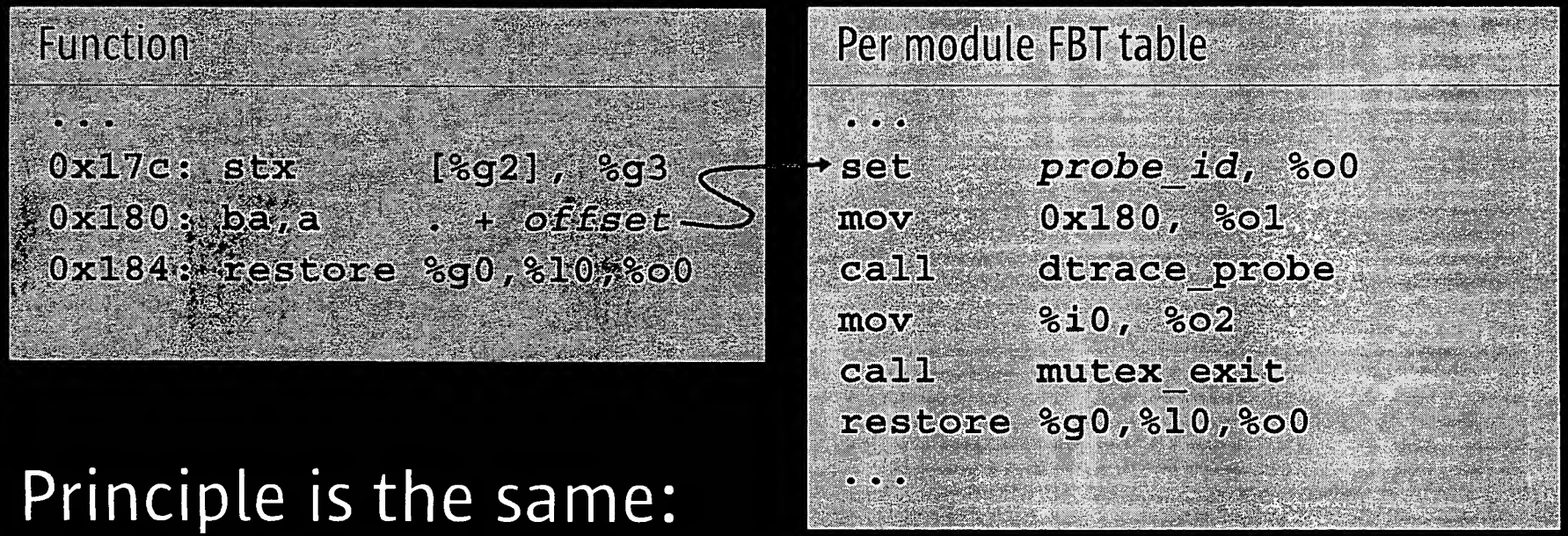
Return Patching, cont.

Function

```
...
0x17c: stx     [%g2], %g3
0x180: call    mutex_exit
0x184: restore %g0,%l0,%o0
```

- ret/restore couplets are not the only way to return from a non-leaf routine
- call/restore and jmpl/restore couplets are used to implement tail-call elimination

Return Patching, cont.



Principle is the same:

- control-transfer instruction is patched to be an annulled branch-always
- Jump table entry performs control-transfer/restore couplet upon return from **dtrace_probe**()

Return Patching, cont.

Function

```
...
0x17c: ldx     [%g2], %g3
0x180: jmpl    %g3,%o7
0x184: restore %g0,%g2,%o0
```

- Both jmpl and restore can operate on register operands

- Must preserve operands volatile across the call to **`dtrace_probe`**() (i.e., inputs and globals)

Return Patching, cont.

Function

```
...
0x17c: ldx     [%g2], %g3
0x180: ba,a    . + offset
0x184: restore %g0,%g2,%o0
```

Per module FBT table

```
...
mov     %g3, %l1
mov     %g2, %l2
set     probe_id, %o0
mov     0x180, %o1
call    dtrace_probe
mov     %i0, %o2
jmpl    %l1, %o7
restore %g0,%l2,%o0
...
```

- The volatile registers are moved into unused locals
- The instructions using the volatile operands are restructured to be in terms of the local

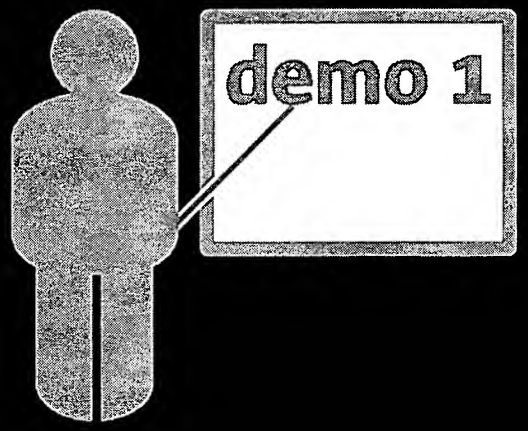
Sun microsystems

Choosing Eligible Functions

- Always err on the side of caution: if a function looks like it's trying to be clever or appears otherwise strange, don't create probes for it
- Only create probes for functions containing both a patchable entry and a patchable return
- (Well, plus `resume_from_zombie()`)

Sun microsystems

dtrace(1M) syntax



dtrace [-i *id*]
[-P *prov*]
[-m [*prov*:] *mod*]
[-f [[*prov*:] *mod*:] *func*]
[-n [[[*prov*:] *mod*:] *func*:] *name*]

Language Design

- The kernel is written in C, so the natural choice for low-level predicates is C:

```
curthread->t_cpu->cpu_id == 0 &&
curthread->t_cpu->cpu_idle_thread ==
curthread ...
```

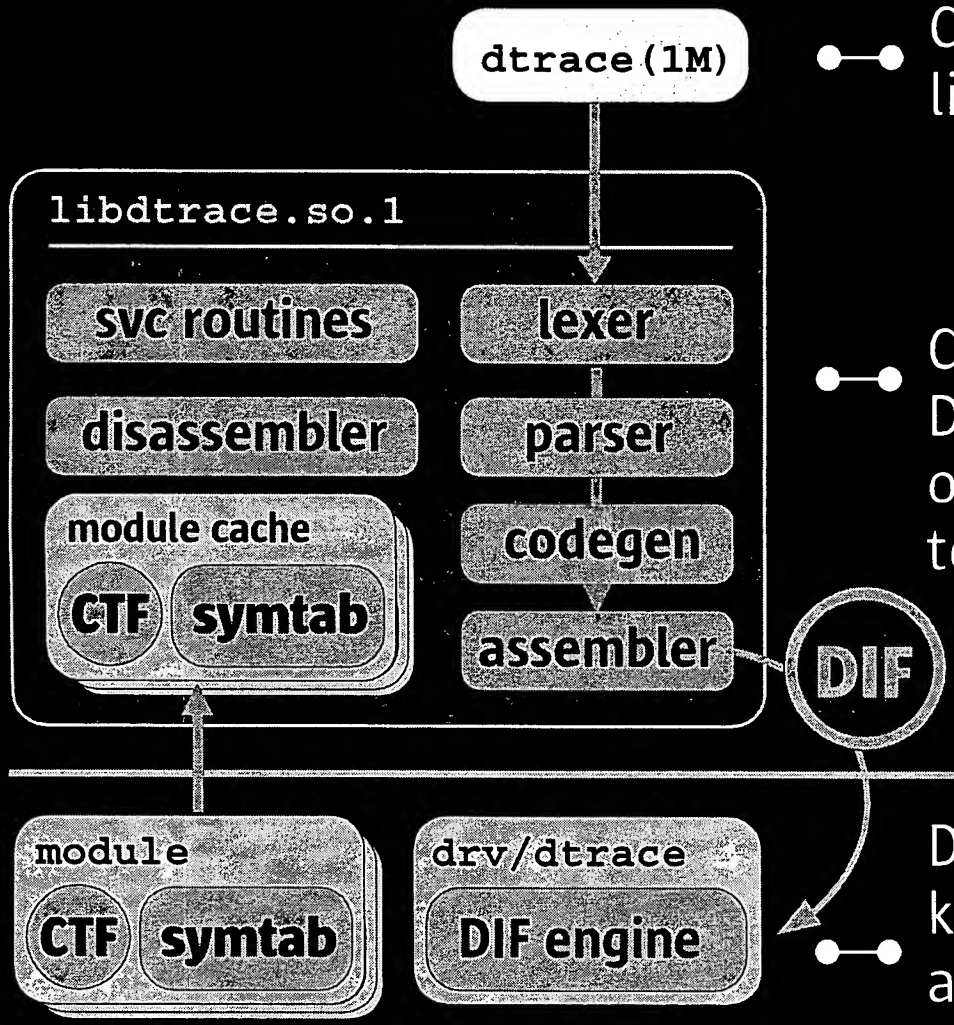
- The Kernel Stabs project (PSARC 2001/021) provided native type info in CTF, so it is possible to build a dynamic evaluator
- Same language for predicates and actions

Sun microsystems

Introducing "D"

- Complete access to native kernel C types
- Complete access to statics and globals
- Complete support for all ANSI-C operators
- Support for strings as a first-class citizen
- Support for built-in variables (timestamp, curthread, arguments, machine regs, etc.)
- Compiler provided as a library API

Implementing D



- Clients send D expressions to library for compilation
- Compiler stack produces D Intermediate Format (DIF) objects that can be bound to probe locations
- DTrace driver stores DIF in the kernel and executes program at probe firing time

DIF Architecture

- Small RISC architecture ideal for simple emulation or on-the-fly code generation
  - variable number of 64-bit registers (%r0 = 0)
  - 64-bit arithmetic and logical instructions
  - 1, 2, 4, and 8-byte safe memory loads
  - standard branches and condition codes
  - instructions to access variables, strings
  - ~50 opcodes, ~200 line emulator (plus some supporting routines for loads, variables, etc.)

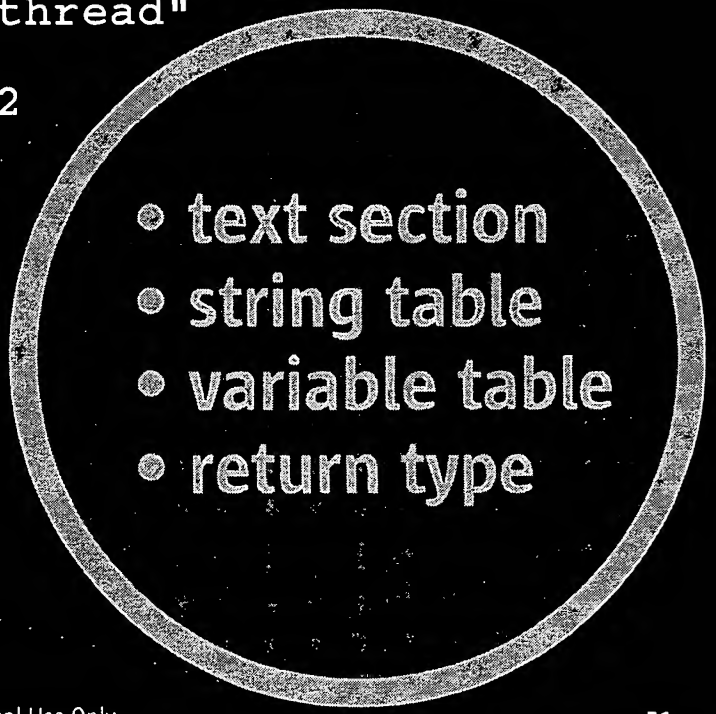
Sun microsystems

DIF Example

- D expression: "`curthread->t_cpu`"
- DIF code:

```
ldgs 256, %r1    ! 256 = "curthread"
setx 0x00000000.000000a8, %r2
add  %r1, %r2, %r1
ldx  [%r1], %r1
ret  %r1
```

- DIF object:



Sun microsystems

DIF Safety

- All DIF objects are validated by the kernel:
  - valid opcodes
  - valid string refs
  - reserved bits must be zero
  - valid registers
  - valid variables
- Only **forward** branches are permitted
- Limit on maximum size of DIF object
- DTrace runtime handles invalid loads, misaligned loads, and division by zero
- DTrace runtime prevents access to i/o space addresses using new vmem arena

Sun microsystems

DIF Load Safety

- DIF engine load routines check alignment and i/o space arena before issuing load
- Per-CPU DTrace fault protection flag is set
- If `hment` search fails and protection is on, sfmmu sets fault flag and issues **`done`** instead of calling `sfmmu_pagefault()`
- Failed load aborts processing of current ECB

Sun microsystems

D Strings

- First-class strings provided to avoid ambiguity of **`char*`** and **`char[]`** in C
- Quoted strings are assigned string type
- Scalars can be promoted to string type using new **`stringof()`** operator
- Operators <, <=, >, >=, !=, == overloaded as strcmp(**3C**); promote **`char*`** and **`char[]`**:

```
curthread->t_procp->p_user.u_comm == "ksh"
```

D Limitations

- Still need to find some solution for #defines that are used as flag bits:

```
(curthread->t_proc_flag & TP_PRVSTOP)
```

- Preprocessor approach possible but messy
- Ideally extend compiler or tools and CTF to support association directly in C source
- Solution would also benefit other debugging tools (e.g. mdb(**1**) **`::print`**)

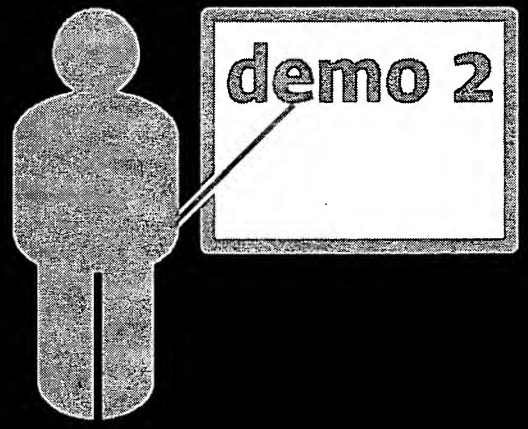
Sun microsystems

Linux DProbes Comparison

- RPN-like IR developed in advance of forthcoming high-level language
- Safety issues not thoroughly considered:
  - user can induce panic if probes are placed improperly
  - user can modify registers, memory, write to i/o ports
  - validation performed in tool and libraries, not kernel
  - infinite loop problem handled by forcing user to specify `jmp_max=123` in probe program

Sun microsystems

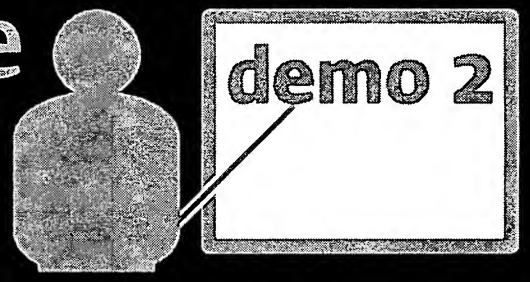
dtrace(1M) syntax



dtrace [-i *id* [*predact*]]
  [-P *prov* [*predact*]]
  [-m [*prov*:] *mod* [*predact*]]
  [-f [[*prov*:] *mod*:] *func* [*predact*]]
  [-n [[[*prov*:] *mod*:] *func*:] *name* [*predact*]]

predact ⇒ [**/** *predicate* **/**] **{** *action* **}**

dtrace(1M) example




```
# dtrace -n 'write32:entry
  / curthread->t_procp->p_user->u_comm == "ksh" /
  { trace(curthread->t_procp->p_pidp->pid_id) }'
dtrace: 'write32:entry' matched 1 probe.
CPU     ID                    FUNCTION:NAME
  0   6796     write32:entry     115575
  0   6796     write32:entry     115575
  0   6796     write32:entry     115575
  0   6796     write32:entry     100392
  0   6796     write32:entry     100392
  0   6796     write32:entry     100392
```

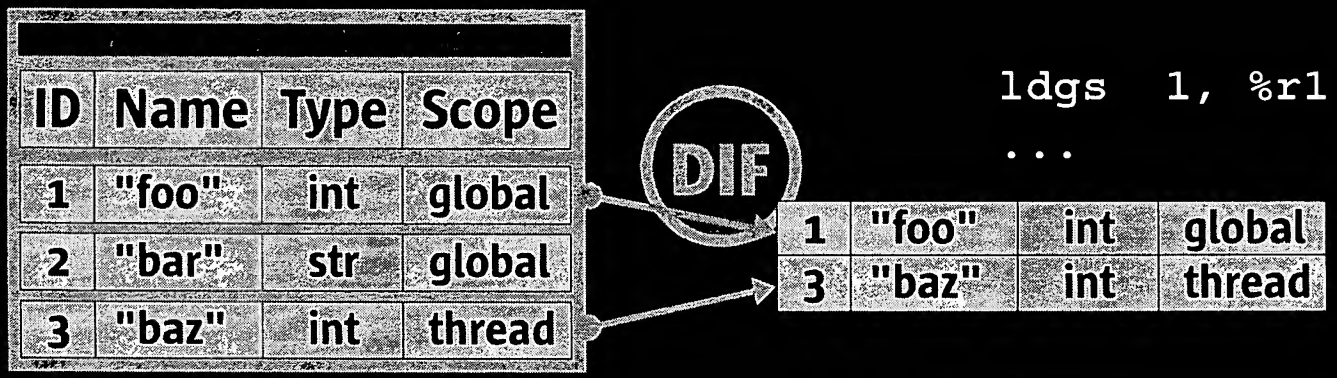
Sun microsystems

Variables

- Idea: allow D actions to instantiate, manipulate, and record variables
- Variables can also be used by predicates to alter control flow and correlate events
- Variable species:
  - scalar variables: integers, strings
  - associative arrays: arbitrary (*key*, *value*) collections
- Variable scope:
  - global per client instance
  - thread-local per client instance

Scalar Variables in D

- Variables instantiated by D assignment operators: `= += -= *= /= %= &= ^= |= <<= >>= ++ --`
- Variable type determined by first assignment
- Variables initially assigned zeroes
- Definitions cached in libdtrace client state



Sun microsystems

Variable Scope

- Global variables named by plain identifiers
- TLS variables accessed and instantiated by overloading "`curthread->`"
- D compiler precedence rules:
  - C type names defined in kernel (ANSI-C rules)
  - DTrace built-in variable names
  - Global and static variable names defined in kernel
  - User-defined variable names

Associative Arrays in D

- Arrays named by *identifier* [*expression-list*]
- Initially filled with zeroes just like scalars
- Entry can be freed by setting it to zero
- Type signature of key and value determined by first assignment; enforced thereafter
- Examples:

```
uids[curthread->t_procp->p_cred->cr_uid]++;
a[curthread, args[0]] = args[1];
```

Value Consistency

- Important to provide semantic consistency for data used in *both* predicate and actions:

```
/ foo == 3 / { trace(foo) }

/ dnlc_nentries < 10 / { trace(dnlc_nentries) }
```

- Kernel data consistency can be achieved by taking a snapshot prior to ECB processing
- Variables pose greater challenges:

```
/ dnlc_nentries < 10 / { foo = 0 }

/ foo++ && bar++ / { trace(foo + bar) }
```

Sun microsystems

Variable Consistency

- Variable group must be self-consistent and consistent w.r.t. other modifying ECBs:

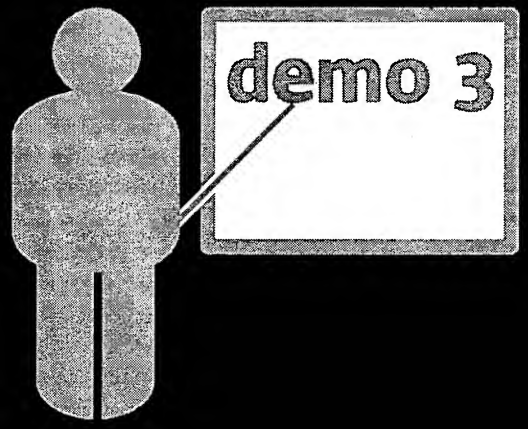
```
/ dnlc_nentries < 10 / { foo = 0 }

/ foo++ && bar++ / { trace(foo + bar) }
```

- Consistency is achieved by locking variables in a defined order (by ID)
- Only need to do this when variables are used in both predicate and action

Sun microsystems

dtrace(1M) syntax



dtrace [-i *id* [*predact*]]
  [-P *prov* [*predact*]]
  [-m [*prov*:] *mod* [*predact*]]
  [-f [[*prov*:] *mod*:] *func* [*predact*]]
  [-n [[[*prov*:] *mod*:] *func*:] *name* [*predact*]]

predact ⇒ [**/** *predicate* **/**] **{** *action* **}**

Aggregations

- An *aggregating function* is a function $f(x)$, where x is a sequence of arbitrary length, for which there exists an aggregating function $f'(x)$ such that:

$$f'(f(x_0), f(x_1), \ldots f(x_n)) = f(x_0, x_1, \ldots x_n)$$

- E.g., COUNT, MEAN, MAXIMUM, and MINIMUM are aggregating functions; MEDIAN, and MODE are not

Sun microsystems

Aggregations, cont.

- When data is to be processed using an aggregating function, the implementation can be made very efficient:
  - Trace records need not be generated; only the intermediate results from the aggregating function need to be stored
  - Intermediate results from aggregating functions can be stored *per CPU*, thereby eliminating data sharing
  - Aggregating function can be periodically performed on all per CPU intermediate results to derive system-wide result

Aggregations, cont.

- An *aggregation* is an associative table keyed by an n-tuple where each value is the result of an aggregating function
- n-tuple consists of a list of D expressions
- Aggregating functions are provided by the framework
- Framework provides a single aggregation per consumer

Aggregations, cont.

- Current aggregating functions:
  - MAX(*expr*): the intermediate result is set to the greater of the intermediate result and *expr*
  - COUNT: increments the intermediate result
  - QUANTIZE(*expr*): the intermediate result consists of 64 power-of-two buckets; the bucket corresponding to *expr* is incremented
  - AVG(*expr*): the intermediate result consists of a count and a total; the count is incremented and the total is increased by *expr*

Aggregation Example

- For example, maximum kernel **`bcopy`**() size by command name:
  - Enable probe with function "**`bcopy`**", name "**`entry`**"
  - Aggregate on:

```
curthread->t_procp->p_user.u_comm
```

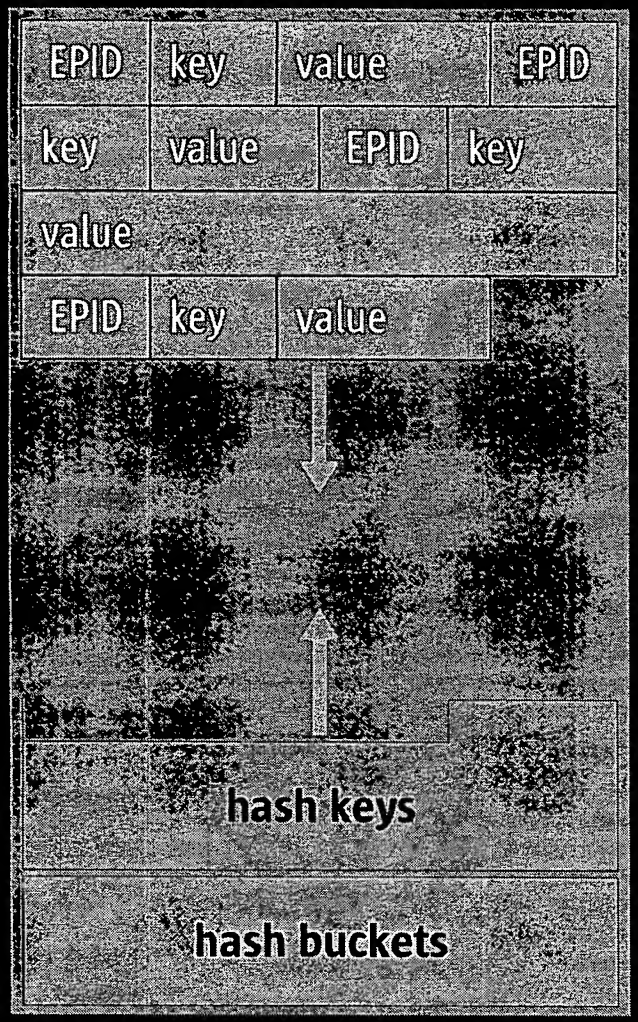
  - Set aggregating function to "**`max(arg2)`**"

Sun microsystems

Aggregation Implementation

- Aggregations are implemented using the same buffer infrastructure as trace buffers
- Buffer switching and copying thus fall out
- Aggregations are an associative table; buffering is complicated by the presence of hash table metadata

Aggregation Implementation



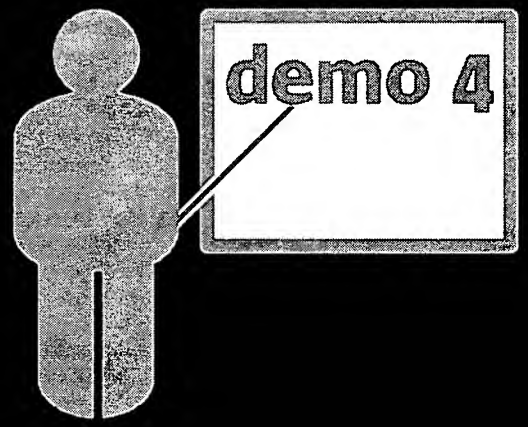
- *Data* grows from start of buffer
- *Metadata* grows from end of buffer
- *Only* data is copied out
- EPID is in data record, but is *not* considered to be part of the key

Sun microsystems

Aggregation Implementation

- Library applies aggregating function to consumed data, using formerly consumed data as intermediate result
- Allows the kernel to discard the metadata contents of consumed aggregation buffers
- Allows drops to be easily eliminated in long-running aggregations

dtrace(1M) syntax



dtrace [-i *id* [a*ggact*]]
  [-P *prov* [*aggact*]]
  [-m [*prov*:] *mod* [*aggact*]]
  [-f [[*prov*:] *mod*:] *func* [*aggact*]]
  [-n [[[*prov*:] *mod*:] *func*:] *name* [*aggact*]]

aggact ⟹ [*/ predicate /*]
  "[" *expr-list* "]" = *aggregating-func* (*arg-list*)

DTrace During Boot

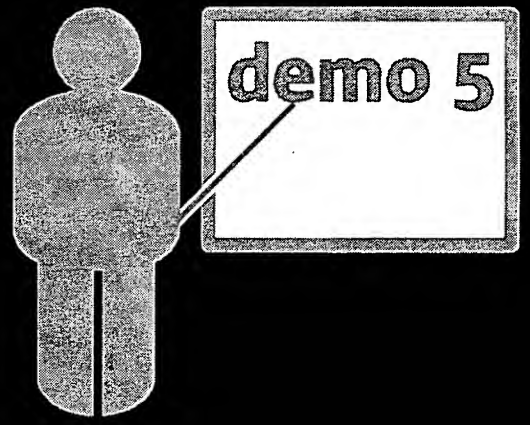
- Normally, consumer is a process with DTrace pseudodevice open
- However, would like to be able to trace during boot — *before* processes can run
- Introduce *anonymous* state:
  - Predicates and actions for anonymous state are specified via driver's configuration file
  - Command has option to generate configuration file
  - Anonymous state may later be *grabbed* by a consuming process

Sun microsystems

DTrace During Boot, cont.

- Use of DTrace during boot revealed that each *text* page for **`libc`** is retrieved from disk three times! (see 4647351)
- Using probe in **`page_destroy`**() with an appropriate predicate revealed source to be calls to **`ufs_flush`**()
- **`ufs_flush`**() is called in **`fsck`**(1M) and again before remount of root filesystem
- Fixing this is a huge win: 8 seconds on X1

dtrace(1M) syntax



dtrace

-a - claim anonymous state

-A - generate .conf file for anonymous tracing

Lockstat Provider

- Lockstat provider implements hot patching of synchronization primitives
- Provides "`block`," "`spin`," "`acquire`" and "`release`" probes for `mutex_enter`(), `rw_enter`(), etc.
- `lockstat`(1M) will be reimplemented as a DTrace consumer
- Long-standing RFEs (e.g., lock statistics per thread or per process) simply fall out

Sun microsystems

Profile Provider

- Provides unanchored probes based on profile interrupt
- Probes implemented as high level cyclics
- Currently no way to specify arbitrary rate; provider makes available ten probes with different hard-coded rates
- Arbitrary rates may be available via private consumer/provider interface

Sun microsystems

TL>0 Provider

- UltraSPARC-specific provider will be implemented to allow probes when trap level (TL) is greater than zero
- Non-trivial: **`dtrace_probe`**() cannot be called from TL>0 context
- Provider will use dynamic trap table interposition, as used in **`trapstat`**(1M), **`ttrace`** and **`atrace`**

Sun microsystems

TL>0 Provider, cont.

- Implementation will be excruciating, but payoff is substantial:
  - Huge quantity of data available via trap table interposition
  - Will benefit enormously from DTrace's ability to prune and coalesce data
- Using technology first developed in `atrace`, TL>0 provider will be able to optionally provide address traces

TL>0 Provider, Cont.

- `trapstat`(1M) will be reimplemented as a DTrace consumer
- **`TRAPTRACE`** will be obviated; equivalent functionality will be dynamic
- Example questions answered:
  - TLB misses per process, per page
  - Window spill traps on a per-function basis
  - All memory references in a specific function for a specific process

Sun microsystems

Probes in C Source Code

- Permit users to define probes in C source as TNF and VTRACE did, but improve syntax:

```
TNF_PROBE_5(strategy, "io blockio", /* CSTYLED */,
            tnf_device,     device,     bp->b_edev,
            tnf_diskaddr,   block,      bp->b_lblkno,
            tnf_size,       size,       bp->b_bcount,
            tnf_opaque,     buf,        bp,
            tnf_bioflags,   flags,      bp->b_flags);
```

- Probe should look like a normal function call
- Enhance compiler to handle code generation and argument type descriptions

Sun microsystems

Traditional Approaches

- D-cache hot but inflexible:

```
if (tracing_on)
    trace(arg1, arg2, ...);
```

- D-cache cold but more flexible:

```
if (this_probe_on)
    trace(arg1, arg2, ...);
```

- Both implementations bloat I-cache footprint

Compiler-Assisted Approach

```
maj = getmajor(bp->b_edev);
...

ldx   [%i0 + 0xa8], %g2   ! bp->b_edev
mov   -1, %g3
srl   %g3, 0, %g3
srlx  %g2, 0x20, %g2
and   %g2, %g3, %g2       ! %g2 = getmajor(b_edev)
...
ret
restore %g0, 0, %o0       ! return (0);
```

Compiler-Assisted Approach

```
TRACE("myprobe", bp);
maj = getmajor(bp->b_edev);
...

ldx   [%i0 + 0xa8], %g2   ! treat as potential call
mov   -1, %g3
srl   %g3, 0, %g3
srlx  %g2, 0x20, %g2
and   %g2, %g3, %g2       ! %g2 = getmajor(b_edev)
...
ret
restore %g0, 0, %o0       ! return (0);
nop                       ! patch point for branch
mov   %i0, %o0            ! assemble probe argument
.stabs "myprobe", id, location, arg-type, ...
```

Compiler-Assisted Approach

```
MACH("myprobe", bp);
maj = getmajor(bp->b_edev);
...

ba,a argsl                    ! branch to arg assembly
mov  -1, %g3
srl  %g3, 0, %g3
srlx %g2, 0x20, %g2
and  %g2, %g3, %g2            ! %g2 = getmajor(b_edev)
...
ret
restore %g0, 0, %o0           ! return (0);
call trampoline               ! jump to trampoline code
mov  %i0, %o0                 ! assemble argument
.stabs "myprobe", id, location, arg-type, ...
```

Sun microsystems

C Probe Applications

- Probes in C source code can be used to convert all kernel ASSERT() instances into probes that can be enabled in production
- Probes can also be placed in C source code to facilitate fault injection testing
- Debug printf code that is not replaced by FBT probes can be replaced with C probes

Basic Block Tracing

- Compiler -xa (tcov) and -xpg (gprof) options generate instrumented code that can be used for basic block coverage, profiles
- DTrace "BBT" provider can be implemented to publish block sites as DTrace probes
- Kernel modules can be compiled using these options for coverage testing
- RIP: uts/common/os/unix_bb.c

Fast-Trap Tracing

- DTrace will reserve fast-trap entry point(s) for tracing user-level activities
- DTrace "FTT" provider can also provide limited access to set of input arguments
- Traps can be generated using handcoded assembly or libc assembly wrapper
- Traps can also be inserted by user-level code generators (e.g. HotSpot JVM)

Sun microsystems

Interface Stability

- Problem: want to allow tools outside of O/N to reliably layer on top of DTrace
- Extend probe description tuple to include probe *stability* (i.e. attributes(**5**) data)
- Most of kernel is Unstable, but DDI routines and types can be Evolving
- D compiler can provide a "lint" mode to warn developers of unstable dependencies

Stable Abstractions

- We can also create more stable abstractions at DTrace API layer, e.g. proc(**4**) structures
- Compiler could provide **`proc_t *psinfo`**
- Library performs necessary transformations:

```
psinfo->pr_flag ⇒ curthread->t_procp->p_flag

psinfo->pr_nlwp ⇒ curthread->t_procp->p_lwpcnt

psinfo->pr_uid ⇒ curthread->t_procp->p_cred->cr_uid

psinfo->pr_sid ⇒ curthread->t_procp->p_sessp->s_sid

...
```

Sun microsystems

Translators

- TNF users burdened with task of translating between abstraction and implementation:
  - ls -lL /dev/dsk/* to deal with dev_t mappings
  - PIDs/LWP ids ⇔ proc_t/klwp_t addresses
  - filenames ⇔ vnode_t addresses, inode numbers
- DTrace could support pluggable translators in or out of kernel to handle mappings
- D compiler can attempt to map predicate to available state by searching for translation

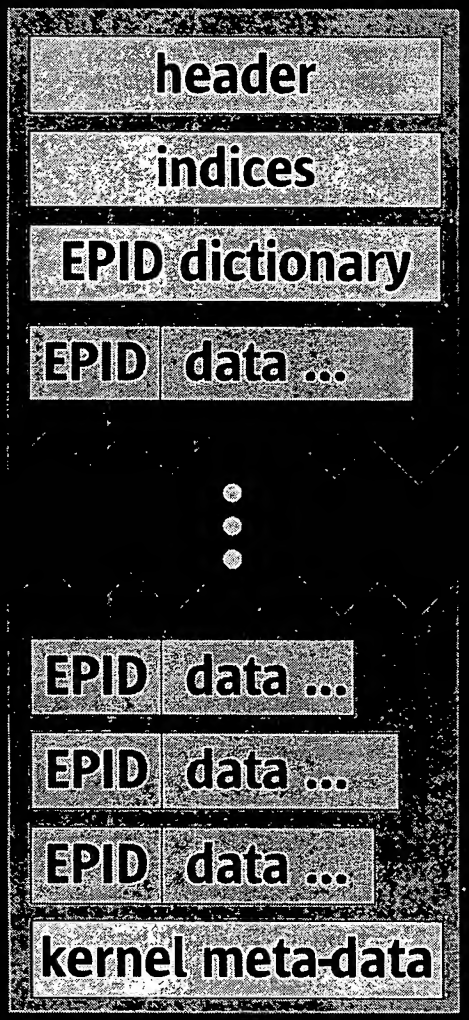
Sun microsystems

Trace Files

- DTrace will provide efficient access to saved trace data and data formatting features
- DTrace library will provide stable API for reading and writing trace files
- Lesson from crash dumps: put *everything* needed to interpret data in the trace file
- Files from one system, OS revision should be readable on another system or OS revision

Sun microsystems

File Format



File header and meta-data for each trace record generated in advance

- ASCII and DIF predicate
- EPID record description
- data length
- data types

Probe data can be streamed out to file using record id while tracing active

- module name, id
- symbol table
- string table
- CTF section

- Module cache of symbol and type data can be written once tracing is complete

Sun microsystems

Conclusion

Feature	GTF	vtrace	TNF	KInst	DProbe	DTrace
user/kernel/merged	M	M	M	K	K	M
probe coverage	●	◒	✗	◒	◒	●
disabled probe effect	○	✗	○	●	●	●
scalability	○	◉	○	○	○	●
safety	●	●	◒	✗	✗	●
extensibility	◒	○	○	◒	◒	●
data filtering	●	✗	✗	○	●	●
arbitrary recording	✗	✗	✗	○	●	●
self describing	◒	○	◒	✗	✗	●
run-time analysis	●	✗	✗	●	◒	●
stock availability	●	✗	●	◒	◒	●
stable abstractions	◒	◒	●	✗	✗	●

Sun microsystems

For more information ...

- Copies of this presentation and other documents available at http://dtrace.eng
- Questions to dtrace-interest@kiowa.eng
- E-mail dtrace-interest-admin@kiowa.eng to join the interest list
- Meetings for near-term consumers
- Project documentation, schedules, and other information forthcoming

Bibliography 1

- Hundt, Robert. "HP Caliper - An Architecture for Performance Analysis Tools." USENIX First Workshop on Industrial Experiences with Systems Software, Oct., 2000.
- Moore, Richard J., "Dynamic Probes and Generalised Kernel Hooks Interface." Atlanta Linux Showcase, Oct., 2000. (see http://oss.software.ibm.com/developerworks/opensource/linux/projects/dprobes/)
- Tamches, Ariel, and Barton P. Miller. "Fine-Grained Dynamic Instrumentation of Commodity Operating System Kernels." Third Symposium on OSDI, Feb., 1999.
- Tamches, Ariel, and Barton P. Miller. "Using Dynamic Kernel Instrumentation for Kernel and Application Tuning." Int'l Journal of High-Performance Applications, Fall, 1999.
- Weaver, David L., and Tom Germond, eds. *The SPARC Architecture Manual, Version 9*, Prentice-Hall, Inc., 1994.

Bibliography 2

- Buck, Bryan, and Jeffrey K. Hollingsworth. "An API for Runtime Code Patching." Int'l Journal of High-Performance Applications, Winter, 2000.
- Dai, Peng, and Thomas W. Doeppner, Jr. "VTRACE and Communication Performance Analysis." Computer Science Technical Report CS-95-36, Brown University, Nov., 1995.
- Hollingsworth, Jeffrey K., Barton P. Miller, and Jon Cargille. "Dynamic Program Instrumentation for Scalable Performance Tools." Proceedings of the Scalable High Performance Computing Conference, May, 1994.
- Johnson, Mark W. "The ARM API, Version 2." Tivoli Systems, Austin, Texas. June 1996.
- Klivansky, Miroslav. "Collecting TNF I/O Traces." Sun Microsystems, Santa Clara, CA. May, 1999.

Bibliography 3

- Larus, James R., and E. Schnarr, "EEL: Machine-Independent Executable Editing." PLDI, June, 1995.
- Srivastava, A., and Eustace, A., "ATOM: A System for Building Customized Program Analysis Tools." SIGPLAN Conference on Programming Language Design and Implementation, May, 1994.
- IBM OS/390 V2R10.0 MVS Authorized Assembler Services Reference, Volume 2 (ENFREQ-IXGWRITE) GC26-1765-13
- IBM OS/390 V2R10.0 MVS Diagnosis Procedures SY26-1082-03
- IBM OS/390 V2R10.0 MVS Diagnosis Reference SY26-1084-09
- IBM OS/390 V2R10.0 MVS IPCS Commands GC26-1754-09

TAB 2

TAB 3

MAPPING OF PENDING CLAIMS TO SLIDE PRESENTATION AND DVD VIDEO

The following mapping should not be constructed to mean that support is only provided in the portions of the Slide Presentation and DVD Video listed.

CLAIM NO.	LIMITATION	SLIDE PRESENTATION	DVD VIDEO*
1	obtaining data from an instrumented program using a probe;	17	0:37:50
	associating the data with an enabled probe identification; and	23 25	0:45:39 0:48:05
	storing the data in the data set, wherein the enabled probe identification is stored in the enabled probe identification component and the data is stored in the associated data set component.	26	0:50:20
2	further comprising:		
	defining a tracing function wherein the tracing function comprises an action;	23	0:45:39
	associating the action with the enable probe identification; and	23	0:45:39
	associating the probe with the enabled probe identification.	23	0:45:39
3	wherein the tracing function is defined by a consumer.	18	0:38:55
4	wherein the enabled probe identification is defined on a per-consumer basis.	23 27	0:45:39 0:51:40
5	further comprising:		

* All times listed under "DVD Video" correspond to the starting time of a portion of the DVD Video, which includes the limitation in question. Further, all times are listed in the following format: HH:MM:SS.

CLAIM NO.	LIMITATION	SLIDE PRESENTATION	DVD VIDEO*
	associating the enabled probe identification with metadata.	26 72	0:50:20 2:28:05 2:30:00
6	wherein the metadata defines the layout of the data.	72	2:23:20
7	wherein the metadata includes at least one selected from the group consisting of an action name, a module name, a data size, a data type, and an action function.	17 46 57 95	0:37:50 1:29:20 1:44:10 3:15:18
8	wherein the enabled probe identification is associated with metadata.	26 72	0:50:20 2:28:05 2:30:00
9	wherein the data set is stored in a kernel-level buffer.	8	0:16:50
10	A method for processing a data set, comprising:		
	copying the data set to a user-level buffer, wherein the data set comprises an enabled probe identification and data;	25 27	0:48:05 0:51:40
	obtaining the enabled probe identification from the data set;	23	0:45:39
	obtaining metadata using the enabled probe identification; and	72	2:28:05 2:30:00
	processing the data set using the data and the metadata.	26	0:50:20
11	wherein the metadata defines the layout of the data.	25 26	0:48:05 0:50:20
12	wherein the metadata includes at least one selected from the group consisting of an action name, a module name, a data size, a data type, and an action function.	17 46 57 95	0:37:50 1:29:20 1:44:10 3:15:18

CLAIM NO.	LIMITATION	SLIDE PRESENTATION	DVD VIDEO*
13	A system for storing a data set, wherein the data set comprises an enabled probe identification component and a data component, comprising:		
	a probe obtaining data from an instrumented program;	17	0:37:50
	a tracing framework associating the probe with an enabled probe identification; and	19 23	0:39:57 0:45:39
	a buffer storing the data set, wherein the data is stored in the data component and the enabled probe identification is stored in the enabled probe identification component.	25	0:48:05
14	further comprising:		
	a consumer defining an action, wherein the tracing framework assigns the enabled probe identification to the action.	18 23	0:38:25 0:45:39
15	further comprising:		
	an EPID-Metadata table relating the enabled probe identification to metadata.	72	2:28:05 2:30:00
16	wherein the metadata includes at least one selected from the group consisting of an action name, a module name, a data size, a data type, and an action function.	17 46 57 95	0:37:50 1:29:20 1:44:10 3:15:18
17	wherein the enabled probe identification is defined with respect to the consumer.	23 27	0:45:39 0:51:40
18	A system for storing a data set, wherein the data set comprises an enabled probe identification component and a data component, comprising:		
	a probe obtaining data from an instrumented program;	17	0:37:50
	a tracing framework assigning an enabled probe identification to an action and associating the probe with the enabled probe	19	0:39:57

CLAIM NO.	LIMITATION	SLIDE PRESENTATION	DVD VIDEO*
	identification; and	23	0:45:39
	a per-consumer buffer storing the data set,	27	0:51:40
	wherein the data is stored in the data component and the enabled probe identification in the enabled probe identification component, and	25	0:48:05
	wherein the enabled probe identification is assigned to the action defined by the consumer associated with the per-consumer buffer.	23	0:45:39
19	further comprising:		
	an EPID-Metadata table relating the enabled probe identification to metadata.	72	2:28:05 2:30:00
20	wherein the metadata includes at least one selected from the group consisting of an action name, a module name, a data size, a data type, and an action function.	17 46 57 95	0:37:50 1:29:20 1:44:10 3:15:18